

Rejecting the Attack: Source Authentication for Wi-Fi Management Frames using CSI Information

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Abstract—Comparing to well protected data frames, Wi-Fi management frames (MFs) are extremely vulnerable to various attacks. Since MFs are transmitted without encryption, attackers can forge them easily. Such attacks can be detected in cooperative environment such as Wireless Intrusion Detection System (WIDS) [1]. However, in non-cooperative environment it is difficult for a single station to identify these spoofing attacks using Received Signal Strength (RSS)-based detection, due to the strong correlation of RSS to both the transmission power (Txpower) and the location of the sender.

By exploiting some unique characteristics (e.g., rapid spatial decorrelation, independence of Txpower, and much richer dimensions) of the Channel State Information (CSI), a standard feature in 802.11n Specification, we design a prototype, called *CSITE*, to authenticate the Wi-Fi management frames by a single station without external support. Our design *CSITE*, built upon *off-the-shelf* hardware, achieves precise spoofing detection without collaboration and in-advance finger-print. Several novel techniques are designed to address the challenges caused by user mobility and channel dynamics. To verify the performances of our solution, we implement a prototype of our design and conduct extensive evaluations in various scenarios. Our test results show that our design significantly outperforms the RSS-based method in terms of accuracy, robustness, and efficiency: we observe about 8 times improvement by *CSITE* over RSS-based method on the falsely accepted attacking frames.

I. INTRODUCTION

Wi-Fi technology is on its rapid evolution. 802.11n standard supports up to 600Mbps throughput, and 802.11i amendment provides strong protection. However, an attacker can still easily launch Denial of Service attack [2]–[4], break the connection between AP and client, establish a rogue AP, and even lead to Man-In-The-Middle (MITM) attack. All these attacks exploit the vulnerability of the 802.11 Management Frame (MF). Unfortunately, MF has always been flying "naked" in the air [5], and anyone can forge the MF easily. IEEE 802.11w introduces encryption-based authentication for several key MFs. However, some researches [6], [7] have identified that 802.11w is still vulnerable to attacks.

The MF spoofing attacks can be easily detected by Wireless Intrusion Detection System (WIDS) or similar systems [8]–[10]. Multiple monitoring stations are required to be deployed throughout the environment to overhear the wireless traffic. They cooperate in monitoring the Received Signal Strength (RSS) for the same MAC addresses. If an anomaly RSS variation appears, an attack is identified by a global decision.

However, such a well secured environment with WIDS is not common. When WIDS information is not accessible, detecting spoofing MF merely based on local information is quite unreliable even in stationary situation. Since RSS highly correlates with transmission power (Txpower) and location [11], [12], an attacker can estimate victim's RSS according to local RSS and distances to genuine station and victim. RSS-based detection therefore can be fooled by scanning Txpower.

In search of a reliable management frame authentication mechanism which supports the operation of a single station, we learned that Intel WL5300 NIC can export another standard PHY-layer information in 802.11n Specification [13], Channel State Information (CSI). The exported CSI reveals the amplitude and phase for each subcarrier of the underlying OFDM system in the form of a complex number matrix. Fig. 1 presents the amplitude of CSI sample. After some proof-of-concept experiments, we believe CSI is ideal for source authentication.

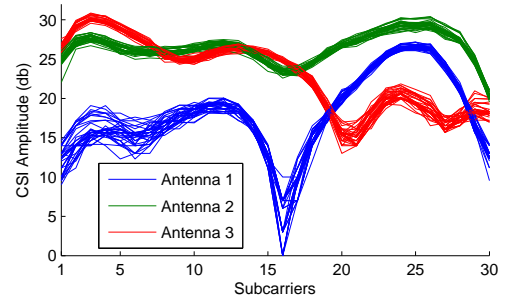


Fig. 1. An example of CSI data. Since Intel 5300agn NIC has 3 antennas, there will be 3*30 subcarriers information for each MAC layer frames. For visual clarity, here we show only 40 frames.

First, the CSI is the reflection of complex transmission procedure of OFDM subcarriers, which involves environment factors, antenna configurations, multipath fading, etc. Due to the complexity, CSI value decorrelates with location quite rapidly. An attacker cannot estimate the victim's CSI according to its own local CSI. Second, CSI reflects the impact of wireless channel on signal propagation, therefore changing Txpower has no influence on CSI. Third, CSI is a high-dimensional data. In a 3×3 802.11n MIMO system, there are 270 values in one CSI matrix. It is extremely difficult to forge

the CSI even with most sophisticated preparation.

Based on such excellent features, we design **CSITE**, a management frame authentication system using off-the-shelf NICs. The idea is simple yet effective: regardless of the frame type, the transmission of both data and management frames between AP and legitimate stations undergoes the same fading and multipathing, which means that their CSI should be exactly similar. If an attacker injects a forged MF, the CSI of this frame must be quite different to the CSI trend learnt from previously accepted frames, thus we conclude that this frame is suspicious.

Our CSITE system is based on a reasonable security assumption that the data frames under strong encryption, i.e. WPA2 with CCMP encryption for a relatively strong password, cannot be cracked in short time [14]. Since an attacker cannot forge a data frame which can be received and correctly decrypted by legitimate station, the encrypted data frames are therefore considered to be sent from genuine station, and their CSI is always trusted. There are three main challenges that should be carefully addressed to make our prototype CSITE work in practice.

First, compared to one-dimensional temporal RSS data, for each frame there is a large complex number matrix of the size $N_{tx} \times N_{rx} \times 30$, where N_{tx} and N_{rx} denote the number of transmitting and receiving antennas respectively. Identifying anomaly data points in such a high-dimensional data stream is a big challenge when the sampling frequency is high.

Second, it is the spatial decorrelation property that makes CSI unforgeable, but this also makes the authentication intolerable to often happened channel dynamics, e.g., those caused by crowd flow or user mobility. To ensure that all potential spoofing MFs are rejected, we will more likely reject many more genuine MFs if the system is not carefully designed for the scenarios with intensive channel dynamics. A mechanism should be carefully devised to guarantee the successful delivery of genuine MF.

Third, the NIC doesn't produce CSI for management frames by default. 802.11n standard provides non-mandatory options to transmit nearly all frames in "HT" rate, which is necessary for measuring CSI. However all MAC layer implementation and drivers still use the old but compatible code which transmits the MFs in legacy format.

Fortunately, since the number of management frames transmitted for normal communication is small, high accuracy CSI-based filter can be achieved without affecting the network throughput. To cope with the channel dynamics, we devise a method called "CSI Resolution Enhancement" (CRE) to ensure the transmission of legitimate MF even under highly intensive channel dynamics. Since it is standard-permitted and technically possible for sending management frames in "HT" rate, we added additional functionalities to the MAC layer implementation and NIC drivers to enable the transmission of management frames in "HT" rate.

In summary, the main contributions of this paper are as follows. We design CSITE, a cross-layer system based on

CSI to perform PHY-layer source authentication for Wi-Fi management frames. In addition to the natural advantages of single-station accurate authentication, CSITE can also cope with user mobility, and no cooperation and no in-advance finger-print are needed for the system. We implement a prototype of CSITE using the off-the-shelf hardware and conduct extensive studies on the performance of our method in various scenarios. Our evaluations show that CSITE has excellent performance on accuracy, robustness, and efficiency. It significantly outperforms the RSS-based method in the same scenarios. For example, when the client and the attacker are walking with regular speed, CSITE accepts some attacking frames with probability about 2%, while RSS-based method accepts attacking frames with probability about 18% for the same scenario. When only the client is moving, we observe similar improvement (about 8 times) by CSITE over RSS-based method on the falsely accepted attacking frames. A significantly better improvement is obtained in stationary scenarios. See Section IV for details. To the best of our knowledge, we are the first to exploit the unique characteristics (e.g., rapid spatial decorrelation, independence to Txpower, and rich dimensions) of *off-the-shelf* platform's Channel State Information (CSI) for authenticating management frames in Wi-Fi networks.

The rest of the paper is organized as follows. Section II presents some preliminaries and reviews related works. Section III describes the CSITE system design. A series of experimental results and analysis are shown in Section IV. We discuss the compatibility and other security issues in Section V and conclude the paper in Section VI.

II. BACKGROUND AND RELATED WORK

In this section we first give a brief review of OFDM, CSI, and 802.11n, which are the foundations of CSITE design. Then a review of related works are presented.

A. OFDM, CSI and 802.11n

802.11a/g/n adopt Orthogonal Frequency Division Multiplexing (OFDM) technology. In OFDM, the overall wide bandwidth channel is divided into many small but orthogonal subcarriers or sub-channels. In 802.11a/g/n, 52/56 (802.11a/g or 802.11n) subcarriers are used to transmit data. Since a channel is divided into many subcarriers, estimating the channel state is equivalent to measuring the parameters for all the subcarriers. In IEEE 802.11n and its successor 802.11ac, Channel State Information (CSI) is a complex number matrix which describes the channel frequency response, each complex value h in CSI matrix could be transformed to polar coordinates that

$$h = |h| e^{j\angle h}$$

where $|h|$ and $\angle h$ denote the amplitude and phase of each subcarrier.

However, not all frames have CSI. Measuring CSI is more complicated than simple RSS measurement. To support such measurement and other PHY-layer features, 802.11n introduces new preamble components (HT-SIG, HT-STF, HT-LTF)

for each frame transmitted in 802.11n "HT" rate format. When *Not Sounding* option in HT-SIG is *false* and HT-LTF (High Throughput-Long Training Field) field exists in the preamble, the NIC will measure the CSI for this frame.

B. Related Works

Numerous researches claim to have the ability to detect MAC-layer spoofing attacks based on RSS or Sequence Number (SN) [8], [15], [16]. However, Txpower can be adjusted to forge the same RSS level, while SN could be forged by following the original pattern. Fingerprint based on hardware transceiver profile is thought to be a perfect solution [17], but advanced attacker using arbitrary waveform generator, can still compromise the fingerprint [18].

Wireless Intrusion Detection System (WIDS) or similar systems [8], [15], [19] can provide reliable attacking detection in secured environment, but these approaches are limited due to the deployment of monitor stations. To the best of our knowledge, the most advanced RSS-based detection is the RCVI [20]. This work cleverly exploits the reciprocity of RSS variance in mobile wireless networks. By detecting the mis-matched RSS variation, an Identity-based Attack (IBA) is detected. However, RCVI require the sender to report the RSS records of the latest received ACK frames, which is a slightly high requirement.

There are growing interests in authentication, location distinction and even localization based on physical layer information. Channel Impulse Response (CIR) has been used to provide robust location distinction in [21], [22]. There are some works [23]–[25] that went further trying to provide precise indoor localization either by identifying the Line-Of-Sight components or by identifying cluster information in CSI.

A new attack against PHY-layer authentication called *mimicry* was identified in [26]. However, such attack is neither easy to launch due to the existence of *symbol sensor*, nor likely to succeed due to the MIMO technique which introduces richer channel information.

III. CSITE DESIGN

In this section, we will first present some of our observations on which the design of CSITE are based. Then the design of CSITE is presented in details.

A. Observation by Testing

A simple injection experiment is conducted to observe the characteristics of CSI. We collected 3000 frames, among which the first 1500 frames are from legitimate station, while the following 1500 frames include frames from both attackers and legitimate station. Fig.2 (a) shows the amplitude of the experiment sample, where different colors denote different amplitudes. We can see the attacker starts injecting a group of attacking frames periodically after the 1500th frame, and the visual difference between normal frames and injected frames is clear.

Fig.2 (b) shows the empirical probability density function (PDF) of subcarrier 20 collected from the first 1500 frames by directly plotting the $Re(h)$ and $Im(h)$ dots, where h is the CSI for this subcarrier. Since the amplitude is stable during the test and the phase is uniformly distributed between 0 to 2π (due to the subjection to Rayleigh Distribution), we observed a ring-shaped structure with narrow width. Fig.2 (c) shows the PDF of all the CSI for subcarrier 20. Due to the amplitude difference between the legitimate and injected frames, a double-ring shaped structure is presented. Such amplitude difference can be used to detect the attacking frames.

B. CSITE Architecture

We are now ready to discuss the architecture of our *CSITE* prototype for authenticating MF frames in Wi-Fi environment.

The CSITE system consists of two parts: *CSITE filter* and *MF transmission assurance system*. The CSITE filter implements our CSI-based spoofing detection algorithm, and its goal is to detect and reject any suspicious MFs. However, the safety and efficiency are always contradictory. In dynamic environment, CSITE filter may also reject some legitimate MFs. In such case, the sender should take measures to ensure the successful delivery of legitimate MFs without compromising the security standard of receiver's CSITE filter, and this is achieved by the MF transmission assurance system.

Since routine data frames are naturally used to update CSI pattern, we don't exert extra burden to network traffic. However to cope with the burst of transmission and asymmetry between uplink and downlink, we set a maximum interval T_{im} between two CSI updates. Once a station has not been updated for a time duration exceeding T_{im} , it will send a ICMP "Probe Request/Reply" probe to force a CSI probe. Then the update frequency, denoted as f_s , of a station would be $\max(1/T_{im}, f_{dl})$, where f_{dl} denotes the downlink data frames frequency.

C. CSITE filter

The mission of CSITE filter is quite clear. Let S_Y denote the frame stream received by a station, and S_Y is composed of three parts: $S_Y = \{S_d, S_m, S_{in}\}$. Here $\{S_d\}$ and $\{S_m\}$ are the encrypted data frame stream and management frame stream sent from genuine station, respectively. $\{S_{in}\}$ is the forged frame stream sent by attackers using injection tools. Our mission is to determine, for a newly arrival management frame M , whether it's sent from genuine station or attacker based on the CSI pattern learnt from S_d . On designing such an filter, there are two technical requirements:

- 1) **Low False Positive (FP) error:** Classifying frames into "legitimate" frames and "suspicious" frames could introduce two errors: wrongfully accepting an attacking frame (called false negative (FN) hereafter), and wrongfully rejecting a legitimate frame (called false Negative (FN) hereafter). Since re-transmission can be launched once a delivery fails, the FN error is tolerable to some extent. However, due to the high risk of successive attacks (*e.g.*,

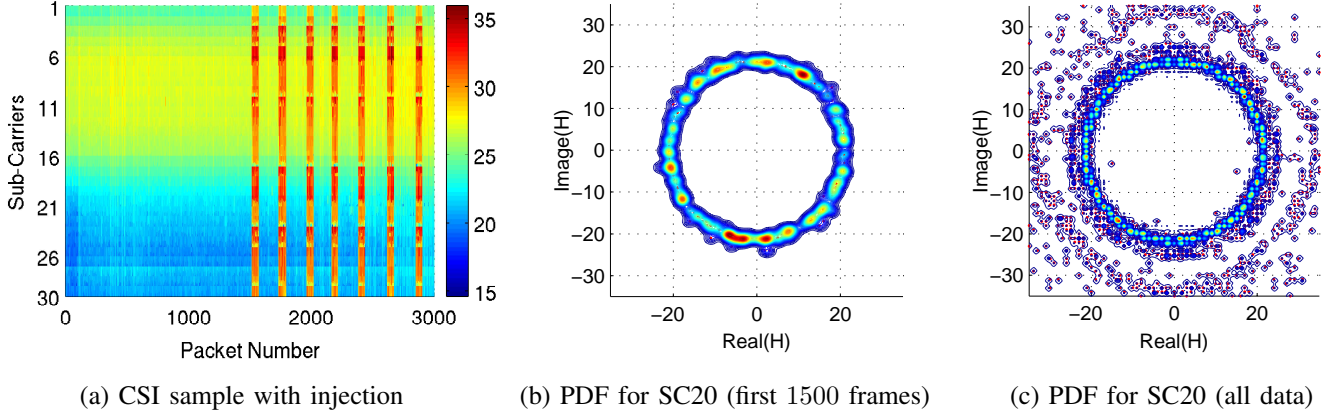


Fig. 2. (a) Amplitude of CSI sample where warmer colors denote larger amplitudes. Attacking frames are injected starting from frame number 1500. (b) PDF for sub-carrier 20 of the first 1500 frames, where the value (denoted by colors) at a point is the number of frames with this CSI. (c) PDF for sub-carrier 20 of all samples, including attacking frames.

man-in-the-middle attacks) triggered by some spoofing attacks, such as de-authentication attack, the FP error is absolutely not acceptable.

- 2) **Low overhead:** In a real world environment, network throughput could be very high, large computation and communication overhead for detecting attacks will significantly degrade the network performance.

Due to the rapid spatial decorrelation, the CSI of spoofing frames are highly probable to be "distant" from the CSI of legitimate frames. Thus, detecting spoofing frames can be viewed as an online anomaly detection problem and the goal is to identify such "distant points".

K-Nearest Neighbour (KNN) [27] is a common solution for high-dimensional anomaly detection [28]. Notice that because a MF frame is said to be a suspicious frame if it significantly deviates from the trend of *most recently* accepted frames, the "anomaly" detection for the problem studied in this paper also needs to consider the temporal distance of the frames. Thus, traditional KNN algorithms cannot be directly applied here.

We design an accurate and effective distance-based spoofing detection algorithm. To reflect the impact of the timing characteristics of all frames, our distance metric takes both spatial and temporal distance into account. An self-adaptive threshold is determined to classify a CSI point into two categories "trusted" or "suspicious". However, before introducing the algorithm, we should first reduce the data point dimension.

Dimensionality Reduction: The dimension of CSI data point is very large, which will consume large computational resource. Even we set the MIMO Tx-antenna $N_{tx} = 1$ and Rx-antenna $N_{rx} = 3$ for our prototype, the dimension of the CSI data point for each frame is $Dim(S_Y) = N_{tx} \times N_{rx} \times 30 = 90$, which is still too large, especially for AP, which is going to handle multiple connections.

As *phase* is uniformly distributed between $-\pi$ and $+\pi$ (due to the Rayleigh Distribution) which provides no discriminative information, the complex number data point Y is first reduced

to a real number data point containing only the amplitude $Y = |Y|$. Since amplitudes of subcarriers exhibit certain continuous structure as shown in Fig.1, we can further merge the adjacent amplitudes. In our system, every 2 adjacent amplitudes are merged to their mean as $(Y_i + Y_{i+1})/2$.

Frame Authenticity Verification:

To verify the claimed authenticity, each receiver holds a sliding window W_r to store the latest verified CSI points with a length L_W . Determining whether a MF is from genuine station is equivalent to determining how distant a MF is from the CSI trend in W_r . If the incoming MF frame perfectly follows the trend, it is highly likely to be a true MF; otherwise it is *suspicious*. We will use the "*degree of following*" (DOF) (exact definition will be given later) to characterize how closely a newly received MF M follows the trend defined by frames in the sliding window W_r . This DOF is determined by two factors: the distance to its k nearest points in the window W_r and the time difference between M 's arrival time t_M and the arrival times of its k nearest points.

Suppose there are n dimensions in each data point after *dimensionality reduction*. We first define the Euclidean distance between CSI point A and B as $dist(A, B) = (\sum_{i=1}^n (A_i - B_i)^2)^{\frac{1}{2}}$. We then define the *following coefficient* between these two points as

$$fc(A, B) = e^{\lambda(|t_A - t_B|)}$$

where λ is a constant called **time gain factor** and t_A denotes the arrival time of point A . We then define the "time-gain distance" between point A and B as

$$tgd(A, B) = dist(A, B) \cdot fc(A, B)$$

Let $N_k^{tgd}(M, W_r) = \{P_1, P_2, \dots, P_k\}$ be the k -NN of M from the sliding window W_r under the TGD distance. The "*Degree of Following*" (DoF) of a new arrival management frame M is then defined as

$$DoF(M) = \frac{\sum_{i=1}^k tgd(M, P_i)}{k}, |P_i \in N_k^{tgd}(M, W_r) \quad (1)$$

Dynamic Threshold Scaling (DTS) : We use threshold τ to decide whether to accept a newly arrived frame M : the M is

considered to be legitimate **iff** $DoF(M) < \tau$. Recall that the premier goal of CSITE is to prevent FP error, the τ should be adjusted adaptively to defend attacks even under highly dynamic environment. Based on a reasonable assumption that the DoF of a newly arrival legitimate MF M is highly probable to be similar to the $DoFs$ of the recently accepted points. Thus in our system τ is determined according to the latest $DoFs$. Let $Q_b(W_r)$ denote the most recently accepted b -th point in the window W_r . Instead of using simple mean or median, the τ is set to i -th percentile of $DoFs$ of recently accepted points, $\hat{\alpha}\acute{e}t$ al.

$$\tau = p_i(\{DoF(Q_b(W_r)) \mid 1 \leq b \leq k\}) \quad (2)$$

where $p_i(S)$ denotes the i th percentile function. Although Eq. (2) requires $k \times L_w$ calculation, it can be optimized by pre-caching the distance matrix between points $P_i \in W_r$ and $P_j \in W_r$.

Here the right selection of percentile i is vital for the system. When there is little channel dynamics, average $DoFs$ of recently accepted frames could be very low. It may cause more FN error (reject the legitimate MF), thus slightly higher i is preferred. While there is intensive channel dynamics, average $DoFs$ of recently accepted frames could be very high. In such case the DoF of a legitimate MF is not necessarily lower than the DoF of an attacking frame, thus lower i is preferred for security concerns. An negative correlation between i and *Channel Stability* is needed.

In CSITE, we define the channel stability σ_W as the mean of the standard variance of the differences between two adjacent CSI points that

$$\sigma_W = \overline{std_n(|P_j - P_{j+1}|)}, n \in [1, Dim(P_i)], j \in [1, L_w - 1]$$

where std_n stands for the standard variance for n th dimension of the CSI in window. We then define a effective negative correlation between i and σ_W as $i_1 = \frac{i_0}{\sigma_W / \sigma_W^r}$, and

$$i = \begin{cases} i_1 & \text{if } i_1 \in [5, 95] \\ 5 & \text{if } i_1 \leq 5 \\ 95 & \text{if } i_1 \geq 95 \end{cases} \quad (3)$$

Here i_0 is set to 75 as default, and σ_W^r denotes the reference σ_W , which is measured during the CSITE initialization and it is adjusted to current σ_W when environment is "stable" (In such condition, the current σ_W is not changing for a time t_σ).

Based on the definition of $DoF(M)$, τ , and i , we design our source authentication algorithm as shown in Algorithm.1.

D. MF transmission assurance system

Due to the rapid spatial decorrelation and the negative correlation between i and σ_W , the CSITE filter is more likely to reject than to accept any suspicious frames. In dynamic environment, it is even harder to classify a MF into "trusted" due to the large noise. How to guarantee the delivery of legitimate MFs in any case is a big problem.

Algorithm 1 Spoofing Frame Detection Algorithm

Input:

The CSI amplitude of a newly received frame Y ;
The encryption property of Y ,
 $attr_{en}(Y) \in \{encrypted, unencrypted\}$

Output:

A security classification of Y ,
 $attr_{sec}(Y) \in \{trusted, suspicious\}$

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1: for each new arrival frame  $Y$  do
2:   if  $attr_{en}(Y) == encrypted$  then
3:     sliding window  $W_r$  move forward to include  $Y$ 
4:      $attr_{sec}(Y) = trusted$ 
5:   else
6:     calculate the  $DoF(Y)$  according to eq.1
7:     calculate the  $\tau$  according to eq.2
8:     if  $DoF(Y) \leq \tau$  then
9:       sliding window  $W$  move forward to include  $Y$ 
10:       $attr_{sec}(Y) = trusted$ 
11:     else
12:       $attr_{sec}(Y) = suspicious$ 

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Despite rapid spatial decorrelation, wireless signal propagation can be well modelled as an analogue continuous system. In this system when sampling rate $f_s \rightarrow \infty$, the differences between each sampling $\Delta D \rightarrow 0$. It means when the frame rates is high enough, we can see very smoothed and slow-changing CSI amplitude surface under intensive channel dynamics. Fig. 3 presents a proof-of-concept experiment. During the experiment, large files are transmitted in HT rate between fast-moving stations, Fig. 3(a) presents the temporal CSI data of a station. When we gradually zoom into the details specified by the black rectangle, we see very smooth surface just like in static environment.

Based on this observations, we design a method called "CSI Resolution Enhancement" (CRE) to guarantee the delivery of MF. The core of CRE is that: if we transmit an unprotected MF M immediately after a group of high frequency "precursor" data frames, there will be smoothed amplitude surface in W_r and receiver's CSITE filter will think it is in a static environment and accept the M by setting higher i . The sender repeats this procedure until the delivery succeed.

Formally speaking, for each MF M we are about to transmit, we define a frame stream $S_j = \{D_0, D_1, \dots, D_{l_j}, M\}$ with minimum transmission interval between frames, where D_i are encrypted data frames. S_j is the j -th transmission procedure. We repeat this procedure until the frame M is successfully transmitted.

Since the proportion of MF in normal communication is very small, we adopt a simple yet robust power-based scheme to guarantee the delivery. Suppose both sides keep the same k and L_W , the expected l_j would be:

$$l_j = 2^j \times (l_1 + 1), j \in (2, 3, \dots, N), l_j \leq L_W \quad (4)$$

This scheme simplifies the problem, and we only need to determine the initial value l_1 . An appropriate l_1 will provide

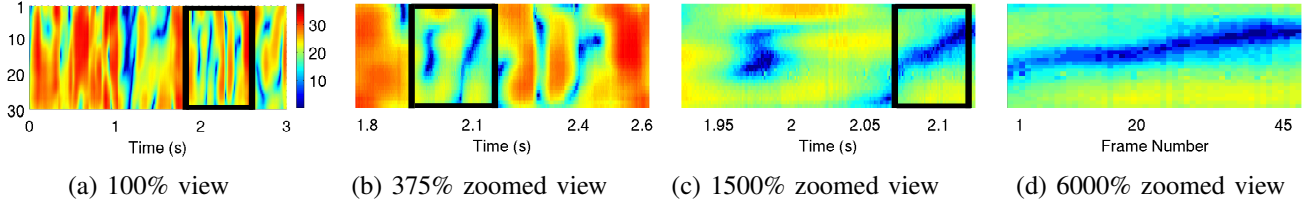


Fig. 3. (a). Original view of CSI under highly dynamic environment. (b), (c), and (d) provide gradually zoomed views for the details circled by black box.

highest "one-shot hit" (successfully deliver the MF by only one transmission) accuracy. In our system l_1 is determined according to a linear relation with respect to the percentile i as

$$l_1 = \delta(L_W(1 - \frac{i}{75})), l_1 \geq 0 \quad (5)$$

where $\delta(x)$ is the rounding function which picks the nearest normal number for x .

Negative ACK encapsulated in Echo Request: There is a firmware-level limit: we have no control on the transmission of ACK frame. The firmware will emit the ACK frame no matter if the frame is rejected by the CSITE filter, therefore transmitter cannot determine if the delivery is successful.

We adopt an *ad hoc* solution to inform the transmitter. Every time a frame does not pass the CSI filter, the receiver will immediately send a *Negative-ACK* to inform the sender. Such N-ACK is carried in a ICMP "ECHO REQUEST" frame whose echo content indicates the failed frame type and sequence number, like "PROBE_REQUEST@42316". Since the frame is encrypted, only genuine transmitter can learn this N-ACK and start re-transmission as described above. However if such N-ACK emits for a spoofing attack, the genuine station will be aware of being forged and may trigger alarm.

We mention again that this *ad hoc* solution exists only because we have no control on the ACK frames.

IV. PROTOTYPE EVALUATION AND ANALYSIS

A. Prototype System Setup

Our prototype system consists of 3 Lenovo laptops equipped with Intel 5300 NICs. Two of them form an AP-Client network with WPA2-AES PSK encryption. The other one acts as an attacker. Their drivers are all modified to enable them to transmit (or inject) management frames in HT rate in compliance to IEEE 802.11n standard.

B. Attacking Test Setting

In order to fully evaluate the performance of CSITE filter and make comparison to RSS based detection, we designed test cases and applied them in 7 typical scenarios. The description of them are presented in Table I. Scenarios A, B, and C test the performance when the client is stationary while channel dynamics are gradually increasing. D to F test the performance when client is moving with different speeds. G presents the final test that both client and attacker are moving.

We run a test for each scenario and each test lasts for 5 minutes. During the test, the AP and the client are continuously

TABLE I
TEST SCENARIOS DESCRIPTION

A	Both the client and attacker are stationary in a controlled environment.
B	Same as A, but there is some channel dynamics caused by crowd flow.
C	The client is stationary, while the attacker is moving around. No crowd flow.
D	The client is moving, while the attacker is stationary. speed is normal.
E	The same as D, but moving speed is slow.
F	The same as D, but moving speed is fast.
G	Both the client and attacker are moving, speed normal.

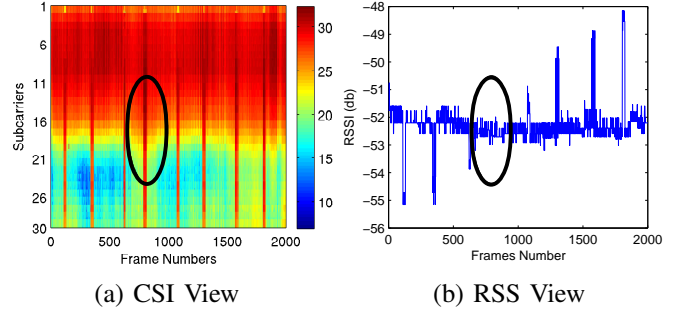


Fig. 4. The CSI amplitude and RSS for the same received frames. The attacker periodically injects a group of attacking frames, and the Txpower is scanning from 1dbm to 15dbm. In RSS view, a group of attacking frames are disappeared, while in CSI amplitude view they are clear.

updating the CSI pattern in highest frequency, 800 fps in average, using the modified *ping* command. The client initiates 20 Probe Requests to the AP every 0.3s, and the AP replies 20 Probe Responses to the client immediately. Both Probe Request/Response are MFs and they formed the un-encrypted stream S_m .

The attacker used *aireplay-ng* to inject 64 forged de-authentication frames to the client every 0.5s using the AP's MAC address. During the attack, the Txpower is scanned from 1dbm to 15dbm in a loop. For the sake of convenience, we set a switch in the client to prevent the connection being really de-authenticated once the client wrongfully accepts the forged de-authentication frames.

For each test case, we mainly focus on two error rates: FP error rate and FN error rate. Specifically, the FP error rate is the number of de-authentication frames which are considered to be sent from legitimate station over the totally received number of de-authentication frames. Similarly, the FN rate is the number of Probe Responses that are considered to be suspicious over the totally received number of Probe Responses.

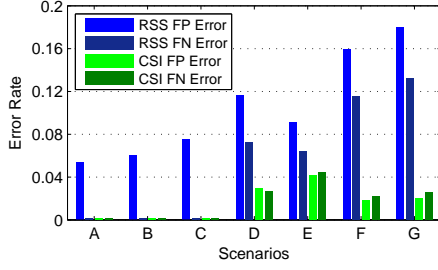


Fig. 5. Error rates comparison between CSITE and RSS-based detection

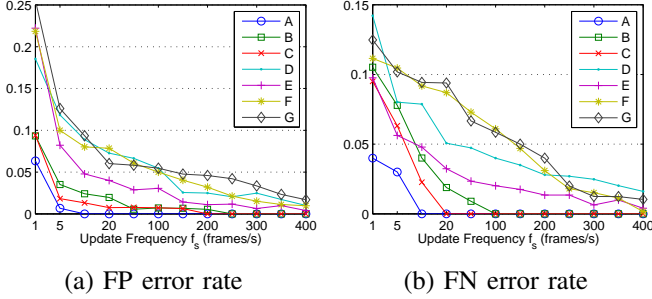


Fig. 6. Impacts of update frequency on detection error rate. Both the FP and FN errors decrease when update frequency f_s is increasing. In Scenarios A, B, and C, both the error rate quickly converge to 0, while for Scenarios D, E, F, G, higher frequency are needed to cut down the error rate.

C. Compared to RSS-based Authentication

Fig.4 presents a real sample in scenario A. The anomaly values periodically emerged in Fig.4(a) and (b) denote the CSI and RSS of the attacking frames. Due to the Txpower scanning, the RSS of the injected frames happens to be identical to the RSS of normal frames at about 800th frames (which is circled in both the CSI and RSS view), and the RSS-based detection fails to detect this group of attacking frames. However, in the CSI view the amplitudes of these attacking frames are stable in about 30 db.

To make a fair comparison between CSITE and RSS-based detection, we turn off the dynamic threshold scaling (DTS) function and set the default value for $i = 75$. Fig.5 presents the error comparison between CSITE and RSS-based detection in different scenarios. In stationary scenarios A, B, and C, CSITE achieves perfect 0 FP error rate, while RSS-based detection yields an FP error rate about 6%. In motion scenarios, CSITE accepts about 2% attacking frames, while RSS-based detection accepts more than 17% attacking frames. It is about 8 times improvement made by CSITE over the RSS-based detection.

D. Impacts of various parameters

To identify the impacts of various parameters, we still turn off the DTS function and use default values $k = 5$, $\lambda = 1$, $L_w = 40$, $i = 75$ for the rest of evaluations if not specifically mentioned.

1) *Impact of update frequency f_s* : To test the impact of f_s , we vary the sampling rate f_s from 1Hz to 400Hz by uniformly dropping frames in the data stream. Fig.6 illustrates the FP and FN error rates in different scenarios when f_s is increasing.

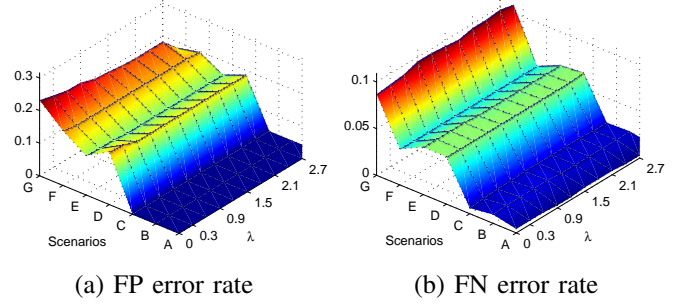


Fig. 9. (a) and (b) show the FP and FN error rates when λ is increasing. In stationary situation, the impact of λ is little. λ begins to take more effect when there is higher channel dynamics.

In stationary scenarios, the FP and FN error rates drop to 0 rapidly when f_s is increasing. For motion scenarios, the FP error rate drops to about 5% when $f_s \geq 100Hz$. When $f_s \geq 400Hz$, the FP error rate is not higher than 3% even under most intensive dynamics in scenario G.

However, we should mention that in normal communication the DTS function is turned on, the CSITE filter could reject almost all attacking frames even when f_s is very low, as verified by our results in *Impact of Dynamic Threshold Scaling*.

2) *Impact of the number of nearest neighbours k* : Fig.7 shows the combined impact of k and f_s on the error rate in scenarios A and G. Since τ is partially determined by the time-gained distance of the latest accepted points, k and f_s play an important role for deciding which points are taken into account. According to Fig.7(a) and (b), higher k could reduce the error rate when in stationary situation. In motion scenarios, however, lower k is better. This is because higher k in this case will introduce more non-related CSI points, which become noises when determining the τ . Based on the test conducted in all scenarios, we believe $k = 5$ is a suitable value for both the stationary and the motion scenarios.

3) *Impact of sliding-window length L_w* : Fig.8 presents the combined effect of sliding-window length L_w and k on scenarios A and G. In both the stationary and the motion situations, increasing L_w is generally good for reducing error rate, but the marginal effect is reduced since the CSITE filter is tuned to choose the most recently accepted points. When $L_w > 40 + k$, the benefit of increasing L_w can be ignored in all scenarios, therefore we set $L_w = k + 40$ for both accuracy and efficiency.

4) *Impact of the time gain factor λ* : Fig.9 shows the impact of λ . The contribution of λ for stationary scenarios is little to decrease error rates. However, higher λ introduces some visible improvements on reducing errors rates in highly dynamic scenarios. In Scenario G, we see approximately 5% FP error rate drop with nearly 2% FN error rate rise.

5) *Impacts of Dynamic Threshold Scaling*: Apparently, lower threshold τ determined by i rejects not only the attacking frames but also some legitimate frames which deviate from the trend center. However, a lower i is preferred since the premier goal of CSITE is to reject the attacking frames.

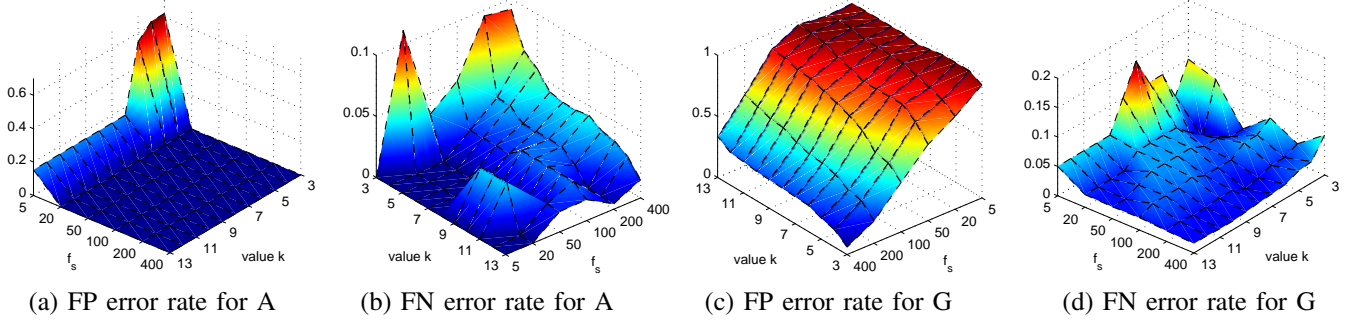


Fig. 7. The combined impacts of value k and update frequency f_s in two scenarios A and G. (a) and (b) show the FP and FN error rates for Scenario A, and (c) (d) for G.

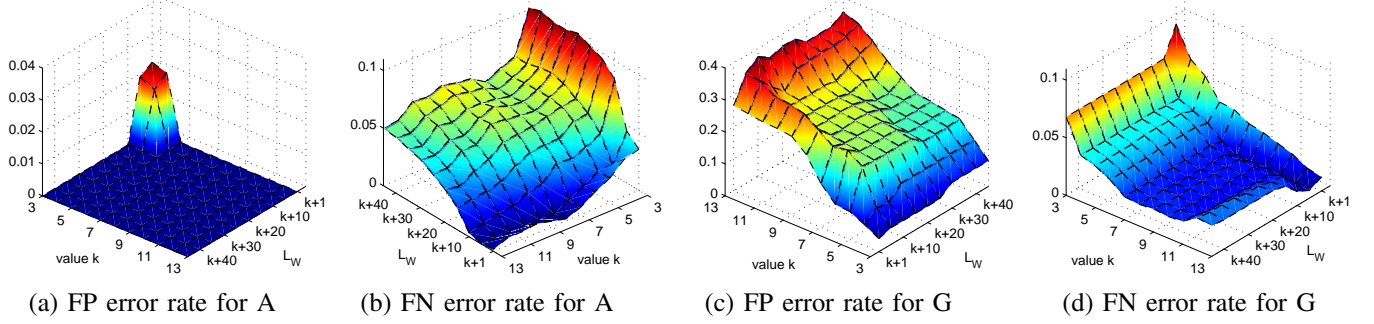


Fig. 8. The combined effect of value k and sliding window length L_w on error rate under two scenarios A and G.

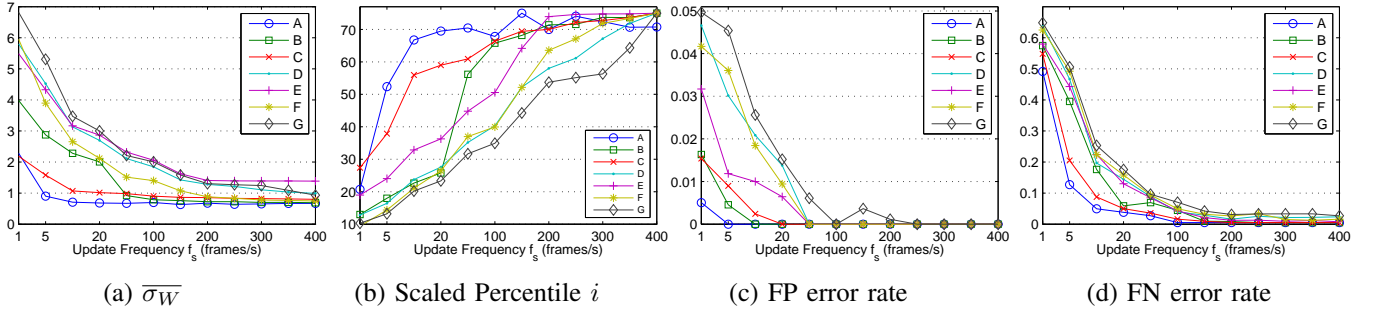


Fig. 10. (a) shows the average window stability $\overline{\sigma_W}$ of 7 scenarios in different f_s . (b) shows the percentile i according to $\overline{\sigma_W}$ and Eq.3. (c) and (d) present the corresponding FP and FN error rates using the percentile i shown in (b).

Recall the *DTS* function introduced in Section III, Fig.10(a) shows the average window variance $\overline{\sigma_W}$ for different scenarios and frequencies. Fig.10(b) shows the dynamic percentile i calculated according to Eq.(3). The impact to the FP and FN error rate is shown in Fig.10(c) and (d). We see that the FP error rates quickly drops to 0 in stationary scenarios. For the most dynamic scenario G, FP error rate drops to astonishingly 5% when $f_s = 5Hz$ at a cost of near 50% FN error rate, and The FP and FN error rates drop to 1.53% and 18% when $f_s = 20Hz$.

E. Evaluation on MF transmission assurance system

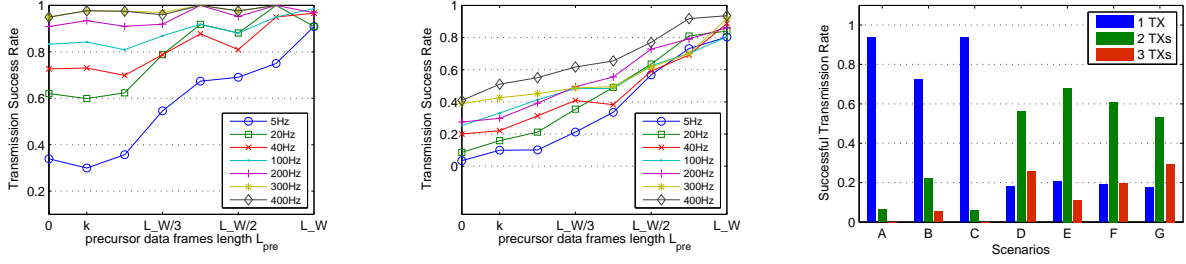
To fully evaluate the transmission of MF in different f_s and scenarios, the data frames before the precursor frames are randomly dropped to simulate different f_s , and the length of precursor frames L_{pre} varies from 0 to L_W .

Fig.11(a) and (b) present the MF transmission success rate comparison with different amount of precursor frames in scenarios A and G. Since *DTS* function is turned on,

many FP errors are generated when f_s is low. However, with the help of precursor frames, we can see that even when $f_s = 5Hz$, with the length $L_{pre} = L_w$, 90% and 78.5% one-shot success (Transmission of M succeeds with only one transmission) rate can be achieved in scenarios A and G. When $f_s = 40Hz$, 97.3% and 90.1% one-shot success rate can be achieved. Fig.11(c) presents the probability of transmission times required to delivery the M . There are more than 95% one-shot success rate in scenarios A and C, and in the most dynamic scenario G, 70% success rate is achieved in first two shots, while over 97% success rate can be done in three shots.

V. DISCUSSIONS

Driver Enhancement: In Intel IWL5300 NIC driver, there are some codes dealing with rate control for different situations. In our prototype, the rate control is modified to transmit the MFs using the same MCS rate of latest successful HT transmission. If it fails (no ACK reply), both precursor data



(a) Successful Receiving Rate in A (b) Successful Receiving Rate in G (c) Probability of Required TX times

Fig. 11. (a) and (b) show in scenario A and G the success rate of MF with different amount of precursor frames. (c) shows the probability of how many transmissions (TXs) are required to successfully deliver the M in different scenarios.

frames and MF will be transmitted in the lowest MCS value in the "BasicMCSSet" to ensure the success delivery. We mention again that these modification is permitted according to the "Multirate Support" in 802.11n Specification [13] Clause 9.6.

Source authentication for control frame: Theoretically, if CSI value can be obtained for control frame, similar source authentication could be applied to control frames. However, it is currently impossible to achieve this goal, since the ACK feedback mechanism is hard-coded in firmware which is a binary file compiled from closed-source code.

Vulnerability of Man-In-The-Middle Attack: Since CSITE detects spoofing MFs based on the CSI of encrypted data frames, if the data frames are replayed in physical layer, Man-In-The-Middle (MITM) attack may succeeded. To launch MITM, the attacker must be able to jam the paired stations and simultaneously tunnel their traffic through the attacker. To detect such attacks, user only need to open a virtual monitor interface. If these is the jamming, the overheard flows to different address will disappear simultaneously, which is impossible in normal situation. This mitigates the impact of MITM attack. However, we believe in most of attack scenarios, such kind of powerful attacker does not exist.

VI. CONCLUSION

Management frame, the basis for operating 802.11 network normally, is extremely vulnerable to attacks. Spoofing detection without cooperative information is unreliable using existing methods. Based on off-the-shelf hardware, we design CSITE, a Wi-Fi management frame source authentication system. It leverages the unique characteristics of CSI to verify the authenticity of MFs, and the detection is tuned to be highly strict to False Positive (FP) errors. To guarantee the successful delivery of MFs even under most intensive channel dynamics, we devise a method called CRE, which makes the MFs pass the detection with the help of precursor frames. Extensive evaluations are conducted to verify the security ability, accuracy, and efficiency. These evaluations show excellent authentication ability and strong rejection against attacks.

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